

Analysing countries' contribution to climate change: scientific and policy-related choices

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Available online 26 September 2005

Abstract

This paper evaluates the influence of different policy-related and scientific choices on the calculated regional contributions to global climate change (the “Brazilian Proposal”). Policy-related choices include the time period of emissions, the mix of greenhouse gases and different indicators of climate change impacts. The scientific choices include historical emissions and model representations of the climate system. We generated and compared results of several simple climate models. We find that the relative contributions of different nations to global climate change—from emissions of greenhouse gases alone—are quite robust, despite the varying model complexity and differences in calculated absolute changes. For the default calculations, the average calculated contributions to the global mean surface temperature increase in 2000 are about 40% from OECD, 14% from Eastern Europe and Former Soviet Union, 24% from Asia and 22% from Africa and Latin America. Policy-related choices, such as time period of emissions, climate change indicator and gas mix generally have larger influence on the results than scientific choices. More specifically, choosing a later attribution start date (1990 instead of 1890) for historical emissions, decreases the contributions of regions that started emitting early, such as the OECD countries by 6 percentage points, whereas it increases the contribution of late emitters such as Asia by 8 percentage points. However, only including the fossil CO₂ emissions instead of the emissions of all Kyoto gases (fossil and land use change), increases the OECD contributions by 21 percentage points and decreases the contribution of Asia by 14 percentage points. © 2005 Elsevier Ltd. All rights reserved.

Keywords: Climate change; Regional historical emissions; Contribution to global climate change; Brazilian proposal; Climate models

1. Introduction

Observations of surface air temperature indicate that a significant global average warming has occurred during the 20th century. Several recent studies have attempted to partition this warming between natural and man-made

causes (Tett et al., 1999; Mitchell et al., 2001) leading the Intergovernmental Panel on Climate Change (IPCC) to conclude that there is strong evidence that man has influenced the climate (IPCC, 2001). More recent studies (Stott, 2003; Zwiers and Zhang, 2003) have further strengthened this conclusion. Furthermore, climate models suggest that future man-made increases in greenhouse gas (GHG) concentrations will cause further climate changes (Cubasch et al., 2001; Johns et al., 2003), which could have

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large impacts on human and ecological systems (e.g. Parry, 2004). International negotiations have led to a first step in combating climate change with the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, but further steps (i.e. emission reductions) are needed in order to achieve the ultimate objective of the UNFCCC of stabilising the GHG concentrations at non-dangerous levels (UNFCCC, 1992).

The issue of allocating these reduction obligations amongst the regions, or Parties of UNFCCC, is called differentiation of future commitments. As part of the negotiations of the Kyoto Protocol, the delegation of Brazil presented one approach for allocating these reductions among OECD countries and economies in transition (the so-called Annex I Parties) based on the effect of their cumulative historical emissions of GHGs included in the Kyoto Protocol¹, from 1840 onwards, on the global-average surface temperature (UNFCCC, 1997). While the Brazilian Proposal was initially developed to further discussions on differentiation of commitments among Annex I countries, it can also be used as a framework for allocating emission reduction burdens across Annex I and non-Annex I countries. The proposal's central idea was that there exists a functional link between GHG emissions and global temperature increase, or other indicators along the cause–effect chain of climate change, such that the indicator can be calculated from the emissions using a simple model or set of models. The indicator acts as a surrogate for climate impacts, which are more difficult to calculate directly. The methodology also assumes that it is possible to apportion the contributions to the change in the indicator between a number of sources and emitters (e.g. nations, regions).

Although it was not adopted during the Kyoto negotiations, the Brazilian Proposal did receive support, especially from developing countries, and the Third Conference of the Parties (COP-3) requested the Subsidiary Body on Scientific and Technical Advice (SBSTA) to further study the methodological and scientific aspects of the proposal. This led to continued debate and analysis (e.g. Enting, 1998; Filho and Miguez, 1998; den Elzen et al., 1999; den Elzen and Schaeffer, 2002; Höhne, 2002; Rosa et al., 2004) and a number of expert meetings organised by the UNFCCC secretariat. The objective of these meetings was to review the scientific and methodological aspects of the proposal and to co-ordinate an intercomparison of attribution results using a set of simple climate models in an exercise called the Assessment of Contributions to Climate Change (ACCC). The conclusions of this analysis are described in UNFCCC (2002b), and some institutes have reported their analysis in more detail (e.g. den Elzen et al., 2002; Andronova and

Schlesinger, 2004; den Elzen et al., 2005; Höhne and Blok, 2005; Trudinger and Enting, 2005).

A follow up exercise is now being carried out by an ad-hoc group for the modelling and assessment of contributions to climate change (MATCH) (Höhne and Ullrich, 2003) to improve the robustness of calculations and more rigorously assess the uncertainties and methodological choices. This paper results from the first activities of MATCH, and addresses the central questions: how robustly can simple climate models (SCMs²) be used to attribute anthropogenic climate change to sources of GHGs (e.g. regional sources) and what effect do a range of scientific choices (related to scientific uncertainties) and policy-related choices³ that are part of the negotiation process, have on these attribution calculations? The effect of some of these scientific choices, such as the input data of historical emissions, or policy-related choices, such as choice of the climate indicator on the attribution results, have already been addressed in some of the references presented above and these results will be reviewed herein. In addition, we present several new attribution calculations with a non-linear carbon cycle, simplified atmospheric chemistry and climate models using non-linear attribution methodologies based on updated historical emissions datasets. Furthermore, this study considers in more depth the remaining gaps in how both policy and scientific choices affect the attribution outcomes. Our approach is to illustrate the effects of making reasonable alternative parameter choices and it is left to future work to rigorously sample the entire parameter space and to provide a review of the underpinning science on which this attribution method is based.

For clarity we note that the term 'attribution' is used in this work to describe the contribution of a given source of emissions (country, country group or greenhouse agent) to a specified indicator of *man-made* climate change. In some sections of the climate change literature (for instance Stott, 2003; Zwiers and Zhang, 2003) the term attribution is instead taken to refer to the fraction of observed global climate change that can be attributed to either natural factors, increasing global GHG concentrations or changes in aerosol particles, rather than to assess the contribution of a group of nations. An analysis of contributions from regions and nations should ideally include all man-made forcing agents (all GHGs, aerosols, albedo change, etc.).

² Simple Climate Models (SCMs) are computationally more efficient than more complex models and can therefore be used to calculate the global mean temperature in response to a large number of different emission scenarios, as has been done in the IPCC-TAR (Harvey et al., 1997).

³ The term 'policy choice' or 'policy-related choice' refers to variables in the calculation, the values of which can not be based on objective ('scientific') arguments alone (den Elzen et al., 2002). As an analogy, consider the use of a time horizon of 100 years for Global Warming Potentials (GWPs). Deciding on which time horizon to use requires a certain level of expert knowledge, but is ultimately a political choice. Although progression in scientific knowledge might shed more light on the consequences of such policy choices, the choices themselves will thus always have to be made largely within the policy context.

¹ Six GHGs or groups of GHGs are covered under the Kyoto Protocol, i.e. carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆).

However, the attribution calculations presented here only account for the Kyoto gases, except for the sensitivity analysis presented later in this paper (Section 3.2.4), in which we also analyse the impact of including emissions of SO₂ and non-Kyoto ozone precursors.

2. Methodologies: calculating contribution to climate change

2.1. Policy-related and scientific choices

2.1.1. Policy-related choices

To calculate the contribution to climate change of sources of GHGs one needs to consider the cause–effect chain from emissions to changes in climate. This cause–effect chain can be described in a simplified form as follows (see also Fig. 1): Emissions of GHGs, precursors and aerosols change the concentration of these and other compounds in the atmosphere. Changed concentrations cause radiative forcing which influences the global average surface temperature. The absolute change in temperature, as well as the rate of its change and its history of change, influences the global average sea level.

The historical perspective is important due to the delays in the respective effects. Many GHGs, once emitted, are only slowly removed from the atmosphere. The resulting radiative forcing causes changes in the global-average surface temperature, again with a certain time delay due to very long term deep ocean response. Fig. 1 illustrates these effects. It shows historical emissions, the effect of the

emissions on radiative forcing, on the temperature and sea level rise. It is assumed that emissions stop today and that the climate system relaxes only slowly towards its original state.

In calculating historical responsibility several policy-related choices have to be made:

Indicator—To calculate the contribution to climate change of sources of GHGs one needs to accumulate the effects of historical emissions using an appropriate indicator along the cause–effect chain from emissions of GHGs to changes in climate. The Brazilian proposal suggested that the global-mean surface air temperature increase should be used, but other indicators would be possible as well (UNFCCC, 2002b) (see Section 3.2.1) (Table 1).

Timeframes—Time choices are important to the calculation of historical responsibility. The first two choices are the *attribution start date* and *attribution end date*, which define the time interval for the emissions that will be attributed to regions (hereafter also referred to as the attribution period, i.e. start date–end date). Emissions that occurred before or after the attribution period are included in the model but not attributed (see Fig. 2). The next choice is the *evaluation date*, which is the time for which attribution is performed. Usually the attribution is determined at the end of the attribution period. The evaluation date can also be after the attribution end date (Fig. 2). This would allow consideration of the long-term effects of emissions, but would only be relevant for indicators that have unrealised effects, i.e. in the cause–effect chain from concentrations onwards, due to the inertia of the climate system (Section 3.2.2).

GHGs and aerosols—Radiative forcing of climate occurs through many different gases and aerosols that are emitted directly or changed indirectly through the emission of other species. In the application of the methods developed here, there is a policy-related choice as to which gases and aerosol (precursor) emissions should be included in the calculations, i.e. which emissions are attributed to the countries/regions and, for these, which sources are attributed (e.g. land use change, see Section 3.2.4). Note that it is possible to include emissions (of particular gases or from particular time periods) in the model calculations without attributing their effects. This would usually be done to give a better match between model simulation and observed global concentrations or temperature, by including emissions whose effects it may not be desirable to attribute (such as sulphate aerosols or early, and therefore uncertain, GHG emissions). These emissions (as well as the effect of all emissions before the attribution period) are depicted as “unattributed” in Fig. 2.

Attribution method—Calculation of regional responsibility is not straightforward, because the climate system is not linear. Some stages in the cause–effect chain are non-linear, and there are feedbacks between different parts of the climate system (e.g. climate change can affect uptake of CO₂ by sinks on land and in the ocean). As a consequence, the

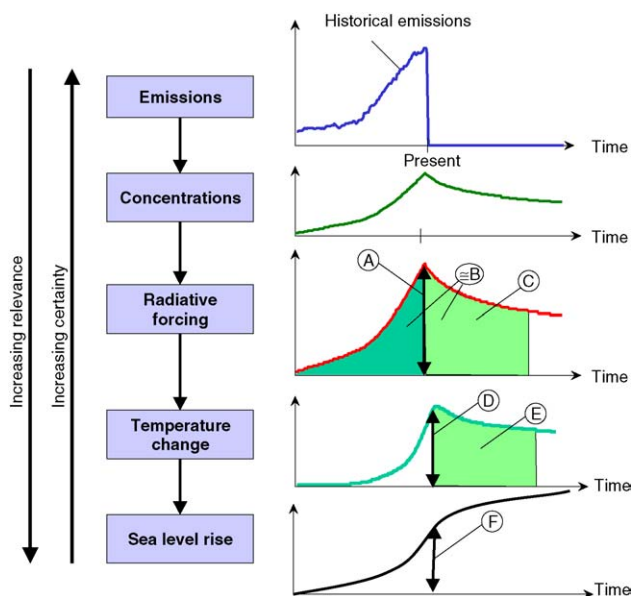


Fig. 1. Schematic diagram of historical emissions and resulting changes in concentrations, radiative forcing, and global-average surface temperature and sea level rise. Letters mark the various indicators. (A) Radiative forcing, (B) GWP-weighted cumulative emissions, (C) weighted concentrations, (D) temperature increase; E: integrated temperature increase; (F) sea level rise, see Section 3.2.1 (figure adapted from Höhne and Blok, 2005).

Table 1

Specifications of the policy and scientific choices of the ACCC exercise, with the default case (underlined> and alternatives (based on ACCC-terms of reference)

Indicators	Radiative forcing, GWP-weighted cumulative emissions, weighted concentrations, <u>temperature increase</u> , integrated temperature, sea level rise
Policy choices	
Timeframes	Attribution start dates 1765, <u>1890</u> , 1950 and 1990 Attribution end dates 1990, <u>2000</u> , 2050 and 2100 Evaluation dates <u>2000</u> , 2050, 2100, 2500
Attribution methods	<u>Normalised marginal</u> , residual, time-sliced
Attributed greenhouse gases (GHGs)	Fossil CO ₂ ^a , CO ₂ [<u>CO₂</u> , <u>CH₄</u> , <u>N₂O</u>], Kyoto-gases (including F-gases, i.e. HFCs, PFCs and SF ₆), Kyoto gases and ozone precursors
Scientific choices	
Historical emissions	CDIAC database (fossil CO ₂ ^b , land-use CO ₂ ^c), <u>EDGAR</u> ^d (Kyoto-gases and ozone precursors) ^e , IVIG-HYDE ^f
Representation of the climate system	See Table 2

^a Fossil fuel CO₂ refers to the CO₂ emissions from energy- and industry-related sources and for the other gases we refer to the anthropogenic emissions, i.e. fossil emissions and emissions from land-use changes and agricultural sources.

^b Marland et al. (1999) (http://cdiac.esd.ornl.gov/emis/tre_glob.htm).

^c Houghton (1999) (<http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html>).

^d The EDGAR CO₂ emissions from land use changes were scaled in order to match with the initial (1990) emissions of the IPCC scenarios (see Section 3.3.1).

^e Van Aardenne et al. (2001) (<http://www.rivm.nl/env/int/hyde>).

^f de Campos et al., 2005.

sum of the effects of emissions from individual sources or regions (considered separately) is not equal to the effect of all emissions together. There are different approaches to attribute the non-linear changes to the different sources (see Section 3.2.3).

2.1.2. Scientific choices

Due to our limited scientific understanding at present, there are several *scientific* choices that have to be made when calculating contributions to climate change. Here we limit ourselves in analysing two scientific choices: the *dataset on historical emissions* (Section 3.3.1) and the *model repre-*

sentation of the climate system (e.g. models describing climate processes, carbon cycle and feedbacks) (Sections 3.3.2–3.3.4 and Table 2).

The options of the policy-related and scientific choices used in this paper are primarily based on the terms of reference of the ACCC exercise (UNFCCC, 2002a). Table 1 gives an overview of the choices (with default values underlined). The results are presented grouped in four global regions taken from the IPCC SRES (Nakicenovic et al., 2000): OECD90; Eastern Europe and Former Soviet Union (EEUR&FSU); Asia (ASIA); Africa, Latin America and Middle East (ALM), and optionally for 13 world regions: Canada, USA, Latin America, Africa, OECD Europe, Eastern Europe, Former Soviet Union (FSU), Middle East, South Asia (including India), East Asia (including China), South East Asia, Oceania and Japan⁴.

2.2. Models

For the calculation of the regional contribution to climate indicators, i.e. concentrations, radiative forcing, temperature change and sea level rise, different climate models are used, which are briefly described below.

ACCC climate model (default)—The terms of reference of the ACCC exercise specifies a simple default model, the ACCC model (<http://www.match-info.net>), that is based on Impulse Response Functions (IRFs) for the calculations of concentrations, temperature change and sea level rise, and based on functional dependencies from the IPCC-TAR

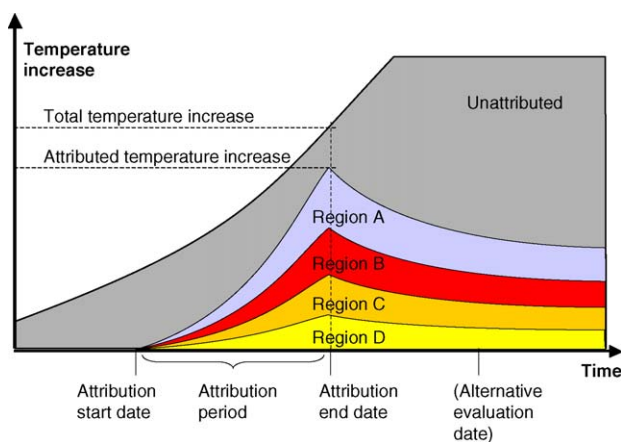


Fig. 2. Temperature increase as a function of time. Emissions within the attribution period are attributed to the regions/countries. Emissions before and after the attribution period, as well as emissions of other gases and agents are included in the model but “unattributed”. Note: the effect of aerosol cooling is not included in this graphic because it is negative (if it were included, the total would be lower than the sum of the regions). Consequently not all temperature increase is attributed to regions/countries.

⁴ For presentation reasons in most of the figures, we have selected only seven regions, representative for (current or future) ‘major’ UNFCCC parties: USA, OECD Europe, FSU, South Asia, East Asia, Africa and Latin America.

(Ramaswamy et al., 2001) for the radiative forcing (e.g. logarithmic function for CO₂). For the CO₂ concentration, the IRF is based on the parameterisations of the Bern carbon cycle model of Joos et al. (1996, 1999), as applied in the IPCC-TAR (Third Assessment Report). For the concentrations of the non-CO₂ GHGs, single-fixed lifetimes are used. The total radiative forcing considered here consists of the radiative forcing from CO₂, CH₄ and N₂O plus direct and indirect radiative forcing from aerosols derived by the coupled ocean-atmosphere General Circulation Model (GCM) HADCM3 (Stott et al., 2000). Surface temperature change, ocean heat uptake and sea level rise are modelled using two-term IRFs also derived from the HADCM3 model. The contributions of individual emissions to concentrations, temperature change and sea level rise are calculated by separately applying all equations defined at global level to the emissions of the individual emitting regions. The assumption of linearity of these steps in the ACCC model ensures that the sum of the regional contributions is equal to the contribution of the global total. The relationship between concentration and radiative forcing is non-linear ('saturation effect'). Here, the normalised marginal method is used as default, as explained in Section 3.2.3.

Seven model groups have implemented the ACCC default model, leading to variations of the ACCC default model: ECOFYS-ACCC (Höhne and Blok, 2005), IVIG-ACCC (Rosa et al., 2004), UCL-ACCC, UIUC-ACCC (Andronova and Schlesinger, 2004), CSIRO-ACCC (Trudinger and Enting, 2005) and RIVM-ACCC (den Elzen et al., 2002, 2005) (Table 2). The UCL-ACCC model differs slightly from the other variants, as it uses an upwelling-diffusion energy-balance climate model (as described below), the CSIRO-ACCC is the only one which does not include the aerosol forcing and the UCL-ACCC uses the cumulative emissions for the attribution (see Section 3.2.3). In addition to these models, two alternative SCMs have been used here, as briefly described below (Table 2). For models that have non-linearities for the relationships between

emissions and concentration, or between radiative forcing and temperature, a non-linear attribution method was used for these steps in the cause–effect chain.

CICERO Simple Climate Model—The CICERO-SCM (Fuglestad et al., 2001), incorporates a scheme for CO₂ from Joos et al. (1996) and an energy-balance climate/upwelling diffusion ocean model developed by Schlesinger et al. (1992). The SCM calculates global mean concentrations from emissions of 29 gases and radiative forcing for 35 components. The CO₂ module uses an ocean mixed-layer pulse response function that characterises the surface to deep ocean mixing in combination with a separate equation describing the air–sea exchange (Siegenthaler and Joos, 1992). It also includes changes in CO₂ uptake by terrestrial vegetation due to CO₂ fertilisation. Parameterisations of tropospheric O₃ and OH as function of NO_x, CO, VOC and CH₄ are taken from IPCC-TAR. Forcings from sulphate aerosols (direct and indirect), fossil fuel black carbon and organic carbon aerosols, biomass burning aerosols, tropospheric and stratospheric O₃ and water vapour are calculated as described in IPCC-TAR and Harvey et al. (1997). The non-linear concentration-forcing relations for CO₂, N₂O and CH₄ (including overlap terms) are from IPCC-TAR.

Java Climate Model (JCM)—The UCL-JCM is an interactive climate model (jcm.chooseclimate.org), including a non-linear carbon cycle model from Bern (similar to that described under CICERO-SCM, but with adjustable physics rather than response functions plus additional temperature feedbacks, see Section 3.3.3), non-linear atmospheric chemistry (as CICERO-SCM), and an adjustable upwelling diffusion energy-balance (UDEB) parameterised to fit seven GCMs (HadCM3 used here) as described by Raper et al. (2001). UCL-JCM includes radiative forcing from all GHGs, ozone, sulphate and carbon aerosols, solar variability and volcanoes (as in IPCC-TAR). A proportional-tracer attribution method was developed, equivalent to the normalised marginal (see Section 3.2.3), to allow retention of UCL-JCM's efficient eigenvector algorithms, and coupling for feedbacks.

Table 2
Specifications of the ACCC models (default) and alternatives of models used

Model	Carbon cycle (CO ₂)	Atmospheric chemistry (non-CO ₂)	Sulphate aerosols	Radiative forcing	Temperature and sea level rise
ACCC (default)	IRF (Bern)	Fixed lifetimes	Hadley	IPCC-TAR	IRFs (Hadley)
ECOFYS-ACCC					
IVIG-ACCC					
UIUC-ACCC					
CSIRO-ACCC	ACCC ^a	ACCC	No	ACCC	ACCC
RIVM-ACCC	ACCC	ACCC or IPCC-TAR	ACCC	ACCC	ACCC or IRFs ^b
UCL-ACCC	ACCC	ACCC	ACCC	ACCC	UDEB ^c
CICERO-SCM	Non-linear ^c	IPCC-TAR	IPCC-TAR	ACCC	EBC/UDO model
UCL-JCM	Bern non-linear	IPCC-TAR	IPCC-TAR	ACCC	UDEB ^c

^a Same methodology used as in the ACCC model.

^b For the alternative calculations in Section 3.3.2.

^c The Upwelling-Diffusion Energy-Balance (UDEB) climate model of Raper et al. (2001).

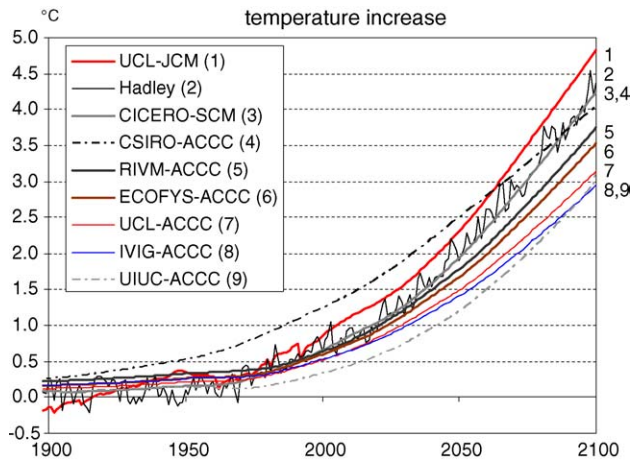


Fig. 3. Comparison of the temperature change calculated with the models used in this paper with the model results of HadCM3, using the SRES A2 scenario. *Note:* the numbers in the figure correspond with the numbered models.

A key requirement of the models used is that they can replicate the historical trends. In the ACCC exercise, results of all participating models, using historical emissions starting from 1765⁵, were compared to the outcomes of a different HadCM3 experiment, which used historical GHG concentrations and sulphate aerosol emissions for the past and SRES A2 concentrations and emissions (Nakicenovic et al., 2000) for the future. The HadCM3 experiment did not include natural forcings, such as solar or volcanic changes, so simulated temperature differs from historical temperature observations. Unlike the simpler ACCC models, the GCM represents internal climate variability so the results are less smooth than for the ACCC models. Fig. 3 shows the spread for historical and future temperature change of the models used in this paper compared to the HadCM3 experiment. As the models differ in their complexity, the temperature curves of the models diverge towards the end of the century. The major differences are due to the inclusion/exclusion of additional forcings. For example, the UCL-JCM model with its extra solar and volcano forcings leads to the highest temperature increase projections, whereas the ACCC variants with only CO₂, CH₄, N₂O and aerosol forcing leads to the lower projections. The CSIRO-ACCC model without the aerosol forcing deviates the most from the historical temperature record.

3. Model analysis

This section provides results of the calculations of contributions to climate change. First, the results of the

⁵ Since EDGAR historical emissions start in 1890, the historical emissions over the period 1765 till 1890 are based on linear interpolation.

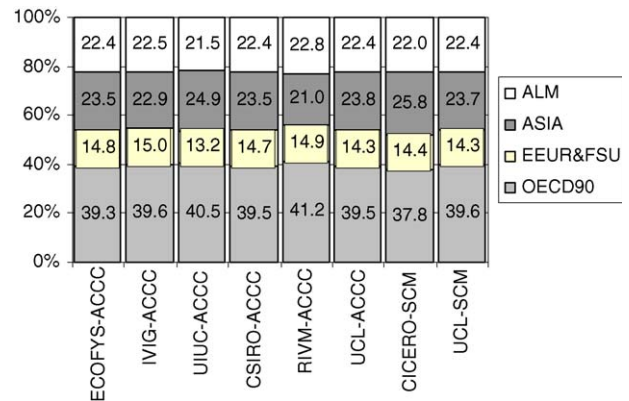


Fig. 4. Comparison of relative contribution to global mean surface temperature increase of the default calculations (Table 1) for each model.

default case are provided, followed by the results considering the policy-related and scientific choices.

3.1. Default calculations

All models described in the previous section provided results for the default case (Table 1: underlined): the relative contribution of four regional groups to temperature change in 2000 using emissions of CO₂, CH₄ and N₂O as provided in the EDGAR database, attributed between 1890 and 2000 (Fig. 4). Most models started their calculations with pre-industrial concentrations and extrapolated emissions back in time so that the models would match observed concentrations better than for a 'cold start' in 1890. Emissions before 1890 were treated as unattributed. Fig. 4 shows a relatively broad agreement between the results from the various models, although a wide range of model-types were used. The difference in absolute temperature change calculated with the models (Fig. 3) is of little influence when determining the relative contribution (Fig. 4). For example, the extra forcings in the UCL-JCM make a large difference to the absolute temperatures, whilst they only have a small influence (via secondary feedback effects) on the relative attribution. To summarise, the average calculated contributions are about 40% (37.8–41.2%) for OECD90, 14% (13.2–15.0) from EEUR&FSU, 24% (21.0–25.8) from ASIA and 22% (21.5–22.8) from ALM.

3.2. Policy-related choices

3.2.1. Choice of climate change indicators

To calculate the contribution to climate change of sources of GHGs, one needs to select an indicator along the cause–effect chain from emissions of GHGs to changes in climate. As indicated in Fig. 1, there is a trade-off between relevance and uncertainty in the choice of the appropriate indicator: on the one hand, the indicator can be close to the actual impacts/damages of climate change if it is chosen further down the

cause–effect chain to obtain a high relevance. On the other hand, it should be calculated with sufficient certainty and therefore be chosen rather at the beginning of the cause–effect chain, since each additional step of the calculation introduces additional uncertainty. The indicator for the contribution to climate change can capture in various ways the differences in timing of emissions and evaluation date. If for a given indicator the effect on climate change is smaller for “early” emissions (that occurred a long time ago) than for “late” emissions (that occurred recently) it could be called ‘backward discounting’. Far distant emissions influence climate today to a lesser extent. The indicator could also be ‘forward looking’, meaning it takes into account the effects of the gases in the atmosphere long after the time of emission.

It is also desirable that indicators are closely related to quantities for which observational datasets exist. This provides an opportunity for validating global total changes giving confidence in the chosen models. Table 3 summarises the characteristics of some of the indicators that are also shown in Fig. 1. Included are only those indicators that can accommodate contributions of different gases. The possible indicator “contribution to concentration” is not included, as it cannot be compared between different gases with respect to their climate effects.

To understand how the different indicators treat historical emissions, we first consider emission pulses in 1900, 1950, 1990 and 2000 and evaluate their contribution to climate change in the year 2000, to study how the different indicators treat “early” versus “late” emissions. Fig. 5 illustrates the results. Table 3 also provides an overview of how the effects of the emissions pulses relate to the effect of an emission pulse of CO₂ in 2000. The table shows the normalised effect of the emission pulses of CO₂, CH₄ and N₂O emitted at different times using the various indicators for contributions to climate change. As shown in the insert in Fig. 5, we define the values of an emission pulse of CO₂ in 2000 as unity and relate to them the values of the effect in 2000 of the earlier pulses and of other gases. A brief discussion of the characteristics of the indicators is given below.

A. *Radiative forcing*: A possible indicator is the radiative forcing in a given year due to the increased concentrations of GHGs (A in Fig. 1). This indicator is ‘backward discounting’ as it accounts for the decay of the GHGs in the atmosphere. CO₂ emissions from the year 1900 are weighted by a factor of around 0.29 of the emissions in 2000 (Table 3). CH₄ emissions from 1900 are almost not counted. This indicator can take into account unrealised effects if evaluated in a year after the emissions have

Table 3

Characteristics of the indicators and weight given in the year 2000 to pulse emissions of CO₂, CH₄ and N₂O emitted at different times using different indicators for contributions to climate change

No.	Name of the indicator	Backward discounting	Forward looking		1900	1950	1990	2000	
A	Radiative forcing due to increased concentrations	X	– ^a	CO ₂	0.29	0.36	0.56	1 ^b	
				CH ₄	0.015	1.0	28	64 ^b	
				N ₂ O	81	126	180	196 ^b	
B	GWP-weighted cumulative emissions	–	X	CO ₂	1	1	1	1 ^c	
				CH ₄	20	20	20	20 ^c	
				N ₂ O	323	323	323	323 ^c	
C	Weighted concentrations	X	X	CO ₂	0.29	0.36	0.56	1	
				CH ₄	0.005	0.31	8.6	20	
				N ₂ O	134	208	296	323	Max year
D	Temperature increase	X ^d	– ^a	CO ₂	3.44	3.92	4.45	1	1983
				CH ₄	9	33	262	64	1991
				N ₂ O	927	1290	1220	196	1976
E	Integrated temperature	X	X	CO ₂	0.90	0.93	1.03	1	1993
				CH ₄	2.2	3.3	16	22	2000
				N ₂ O	189	260	327	324	1994
F	Ocean heat uptake	X ^d	– ^a	CO ₂	240	160	33	1	<0
				CH ₄	3600	4600	2100	64	1962
				N ₂ O	67000	46000	8300	196	1684

Values for each indicator calculated in the year 2000 are normalised to that of the pulse emissions of CO₂ in 2000. For those indicators where emissions before 2000 are more weighted than emissions in 2000, the year that is weighted the maximum is provided in the last column (adapted from H $\ddot{o}$ hne and Blok, 2005).

^a Can be made forward looking, when evaluating at a date after attributed emissions end. In such case also a time horizon is required.

^b Represent instantaneous GWPs.

^c Represent GWPs. Values slightly different to those of IPCC-TAR due to use of different parameters.

^d Also discounting most recent emissions.

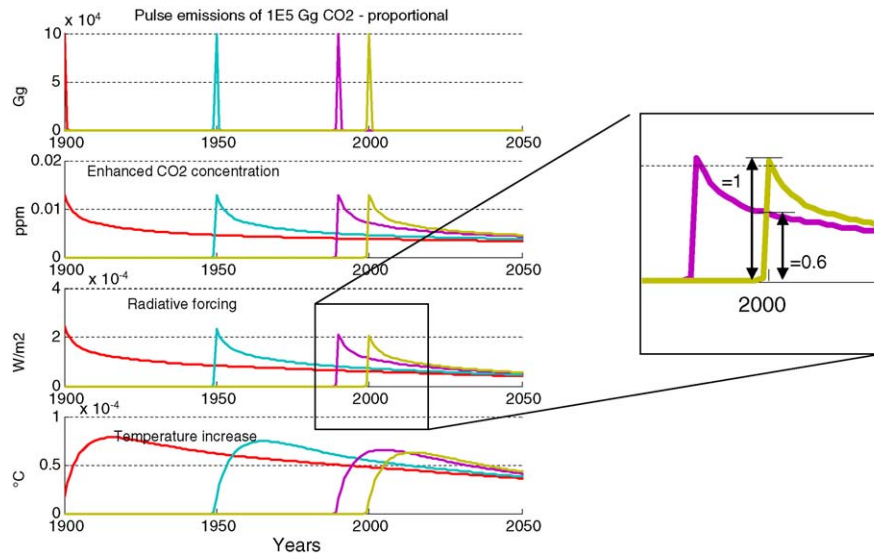


Fig. 5. Emissions, concentrations, radiative forcing and temperature increase for four emission pulses (Höhne and Blok, 2005). Pulses are calculated with the ACCC default model and therefore non-linearities are included only at the radiative forcing step.

stopped (evaluation date after the end of the attribution period) (see Section 3.2.2).

- B. *GWP-weighted cumulative emissions*: Adding cumulative historical emissions using GWPs⁶ (B in Fig. 1) would be ‘forward looking’, since the calculation of the GWP involves the integration of the radiative forcing over a time horizon after the emission. The choice of the time horizon alters the relative weight of short-lived versus long-lived gases. For any time horizon, the fast decay of methane gives it less weight compared to indicator A (radiative forcing). The ratio for the year 2000 is 1 (CO₂) to 20 (CH₄) to 323 (N₂O) (Table 3). The values shown here represent the GWP values as calculated with the ACCC default model.⁷ This indicator is, however, not ‘backward discounting’, meaning that emissions at any time within the considered period are given the same weight.
- C. *Weighted concentrations*: As another way to account for the future effects, Höhne and Blok (2005) proposed to integrate the radiative forcing over time, that is due to today’s increased concentration from today until a point in time in the future (letter C, Fig. 1). The historical responsibility would be calculated using today’s

increased concentration, assuming it would decay in the present atmosphere according to its adjustment time and integrating the resulting radiative forcing over a period from today into the future. Thus, this indicator is similar to the GWP and is therefore called ‘weighted concentrations’. This indicator is ‘backward discounting’ to the same extent as is radiative forcing (compare CO₂ rows in Table 3), but the indicator is also ‘forward looking’ and gives the weight to different gases emitted in 2000 as the GWPs do (compare 2000 column in Table 3). The short lifetime of methane is therefore taken into account twice (i.e. in the past and in the future) and decreases its weight, if this indicator is used.

- D. *Temperature increase*: A further indicator, which is easily recognisable by policymakers and relevant to impacts, could be the increase in global average surface air temperature as proposed in the original Brazilian proposal (UNFCCC, 1997). This indicator is ‘backward discounting’. In fact, it is to a certain extent weighing the most recent emissions less, due to the delay between emissions and temperature increase. Using the ACCC default model, the delay from pulse emissions to the maximum effect on temperature is 16 years for CO₂, 9 year for CH₄ and 24 years for N₂O. Consequently, CO₂ emissions from 1990, 1950 and 1900 are weighted higher than emissions in 2000 (Table 3). The ratio between emissions of different gases in 2000 is the same as for radiative forcing. This indicator can be made ‘forward looking’ to capture the delay effect, by considering the effect of emissions until today on the temperature at a point in the future (Section 3.2.2).
- E. *Integrated temperature*: Another way to overcome the characteristic that temperature increase is not forward

⁶ Calculated as CO₂-equivalent emissions, calculated using the emissions of the six Kyoto gases combined with the 100 year GWPs (IPCC, 2001). Since the introduction of the GWP concept (1990), it has been subject of continuous scientific debate on the question of whether it provides an adequate measure for combining the different effects on the climate system of the different GHGs (e.g. Fuglestad et al., 2003). However, despite its limitations, the GWP concept is convenient and has been widely used in policy applications such as the Kyoto Protocol.

⁷ Compared to IPCC GWP calculations, the ACCC default model does not include indirect effects of methane and uses a different decay function for CO₂.

looking is to integrate the increased temperature over a period of time into the future, assuming emissions stop today. Such an indicator is based on the concept that the level and duration of temperature increases is relevant for climate change damages. One option (not presented here) would be to integrate temperature increase from the past to the future. In this case, the indicator would however not be ‘backward discounting’ as only additional contributions are added as time progresses. The option presented here integrates only from present into the future (letter E in Fig. 1) and is therefore ‘backward discounting’ and ‘forward looking’.

This indicator still has the delay effect as temperature increase, but to a much lesser extent (up to 3% and up to 7 years delay, see Table 3). It discounts backwards slower than weighted concentrations and radiative forcing, because it considers a second ‘memory’, the energy in the climate system. Methane from 1900 is still weighted with a tenth of its value for 2000, while for radiative forcing it would almost not be counted. On first sight it is astonishing that the weight given to CH₄ and N₂O for 2000 is very similar to the 100-year GWP values. In fact, the formulas for integrating future radiative forcing and integrating future temperature change are very similar. For very long time constants for the climate system they almost converge (see also Shine et al., 2005 on Global Temperature Potentials).

- F. *Ocean heat uptake and Sea level rise*: Some climate variables respond on very long time scales, such as ocean interior temperatures, which can take several hundred years to respond to a radiative forcing. This means that ocean heat uptake and sea level will also respond very slowly. The total sea level rise also depends on the melting of land ice, which adds further uncertainty and time constants. In this paper we have chosen to calculate only ocean heat content for simplicity.

A serious implication of using either of these indicators is that the delay effect of this indicator is even more pronounced than for temperature increase. As a consequence, the weight on the short-lived gas methane is relatively high. In addition, most recent emissions are weighted less. The delay from pulse emissions to the maximum effect on ocean heat content is larger than for temperature increase (more than 2000 years for CO₂, 38 year for CH₄ and 316 years for N₂O, Table 3). As it is not ‘forward looking’, the ratio between emissions of different gases in 2000 is the same as for radiative forcing and temperature increase. To capture the delay effect, one could consider the effect of emissions until today on the temperature at a point in the (far distant) future (see Section 3.2.2).

- G. *Other indicators*: Other indicators, such as the rate of increase in the global-average surface temperature, damage in monetary terms or discontinuous functions, such as an abrupt change in the thermo-haline circulation, could also be used, but are not further

considered here. Each of these indicators would add additional complexities and are left for further study.

It should be noted⁸, that choosing any indicator which is a non-linear function of forcing (for example, temperature raised to an exponent, as used in some economic models) may complicate the attribution methodology and calculation algorithms, because the effects of different gases and aerosols would no longer be independent (i.e. the emissions of one gas could change the attribution due to another).

Fig. 6 presents the contributions of different gases and regions for various indicators in 2000 from emissions starting in 1890 using the ECOFYS-ACCC model. Two main factors influence the difference in the contributions of regions using the different indicators: (a) whether emissions were emitted ‘early’ versus ‘late’ and (b) the share of emissions of short-lived gases. The indicators ‘weighted concentrations’ and ‘integrated temperature’ take into account the short lifetime of methane twice and therefore give lowest weight to this gas (Fig. 6). Regions with high share of methane (e.g. ASIA) therefore have a lower weight using these indicators compared to using other indicators. Temperature increase and even more ocean heat content give emphasis to past effects; therefore methane has a high share using these indicators. For early emitters, contributions are reduced by choosing an indicator that decreases the time lag between emission and impact as measured by the indicator. Thus contributions of, e.g. OECD90 (which tend to be “early” emitters) are lower for radiative forcing as an indicator, than for temperature increase, or sea level rise.

3.2.2. Timeframes

It is important to note that the Brazilian Proposal can be applied to any period of time. The choice of the attribution start- and end dates leads to different shares of responsibilities for groups of countries and is therefore an important aspect for policy makers (Rosa et al., 2004).

The following three policy-related choices must be made regarding the time frames: (1) attribution start date; (2) attribution end date and (3) evaluation date of attribution calculations. The time-frame parameters are illustrated in Fig. 2.

First, we will illustrate the dynamics of the ‘memory’ of the system to provide a context for the analysis on time frame in the subsections below. Fig. 7 shows the contribution of total anthropogenic CO₂ emissions from various historical time periods to the enhancement in total CO₂ concentration (compared to pre-industrial levels), radiative forcing and temperature increase. The decay function for CO₂ used here assumes relatively fast decay in the first 100

⁸ This issue does not apply to the temperature and ocean heat content since these are both calculated as linear functions of radiative forcing. Additional climate-carbon feedbacks as introduced in Section 3.3.3 lead to a small interaction between the forcing from different gases.

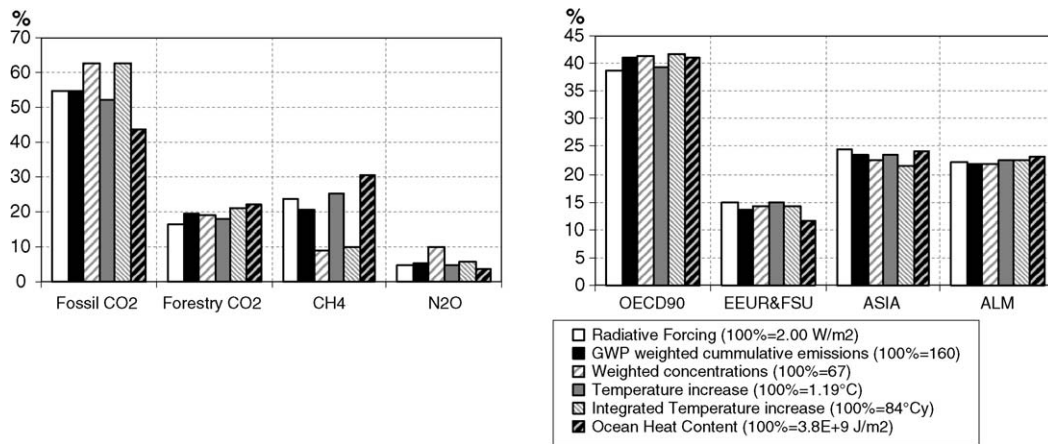


Fig. 6. Contribution of historical fossil CO₂, forestry CO₂, CH₄ and N₂O (left panel) and for the four IPCC regions (right panels) for the attribution period (start date–end date) 1890–2000 evaluated in 2000 using different indicators. *Note:* explanation of 100%: For example radiative forcing, the emissions within the attribution period for all sources leads to 2.00 W/m², and the fossil fuel CO₂ emissions with a ~53% contribution leads to ~1.06 W/m². Source: ECOFYS-ACCC.

years (70% of CO₂ is removed within 100 years) but slow decay afterwards (20% still remains in the atmosphere after 650 years). Using the ECOFYS-ACCC model, we calculate that the CO₂ emissions from 1750 to 1900 are responsible for 9.4% of year 2000 CO₂ radiative forcing and 12.8% of the temperature increase due to CO₂. Indicators further down the cause effect chain, e.g. integrated temperature or sea level rise, account for more “memory” and, therefore, will result in higher relative contributions of the emissions from 1750 to 1900.

We can illustrate the effect of *attribution start date* on attribution of temperature increase in 2000 by considering a range of start dates between 1765 and 1990 (Fig. 8). The

results of the RIVM-ACCC model show the start date to have a strong impact on the regional contributions. Fig. 8 also presents the results at the level of seven selected regions. Choosing a later attribution start date (e.g. 1950 or 1990 instead of 1890) minimises the relative contributions of the industrialised countries (‘early emitters’) to temperature increase in 2000. An exception is the FSU, for which the relative contribution increases for start date 1950, since their rate of emission growth is low compared to the OECD90 over the 1900–1950 period.

We also illustrate the sensitivity to *attribution end date*. We have taken 1890 as default attribution start date, but 2100 for the evaluation date, since it should be at least after the attribution end date. Fig. 9 illustrates the regional contribution to global temperature increase for different attribution end dates between 1990 and 2100. The attribution end date has a strong impact on the relative contribution of the temperature increase of most regions. Choosing a point in time further into the future lowers the relative contributions of Annex I regions and raises those of non-Annex I regions, especially those with fast-growing emissions after 2000. Note that attribution end dates after the present attribute the effect of emissions from a future emissions trajectory, not just historical emissions. Using a different IPCC-SRES emission scenario, also shown by the bars in Fig. 9, does not fundamentally change these general observations regarding the impact of changing the end date. However, it has a strong influence on a region’s relative contribution to temperature change in 2100. The share of developing regions in the temperature increase will increase when high economic growth is combined with a diminishing economical gap between Annex I and non-Annex I regions.

The third time-frame choice is the *evaluation date*, the year in which the attribution calculations are performed; see Fig. 2 (default value 2000). Using an evaluation date after the attribution end date, captures the delayed effects in the system and accounts for delayed, but inevitable, global

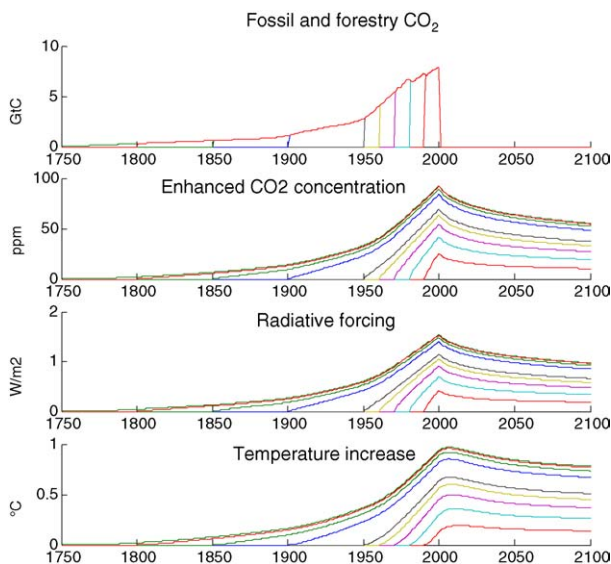


Fig. 7. Historical emissions of CO₂ only and its impacts on concentrations, radiative forcing and temperature change using the ACCC default model. Individual curves represent contributions of emissions from 1750, 1800, 1850, 1900, 1950, 1960, ... to 2000 (labelled ‘a’ to ‘j’). Source: ECOFYS-ACCC, adapted from Höhne and Blok (2005).

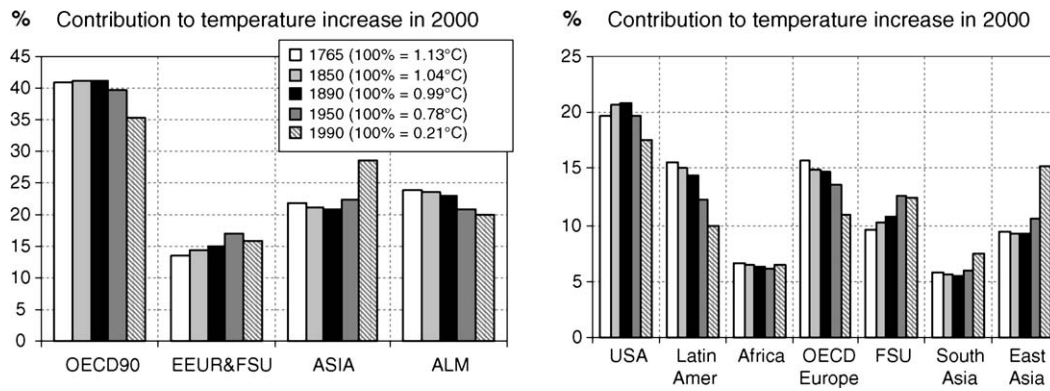


Fig. 8. Regional contributions to the global-mean surface temperature increase in 2000 for alternative attribution start dates cases (including the reference case 1890; attribution end date 2000) for the four IPCC regions (left panel) and seven selected regions (right panel). Numbers given in parentheses in the legends show the magnitude of the warming that is subject to attribution. Source: RIVM-ACCC.

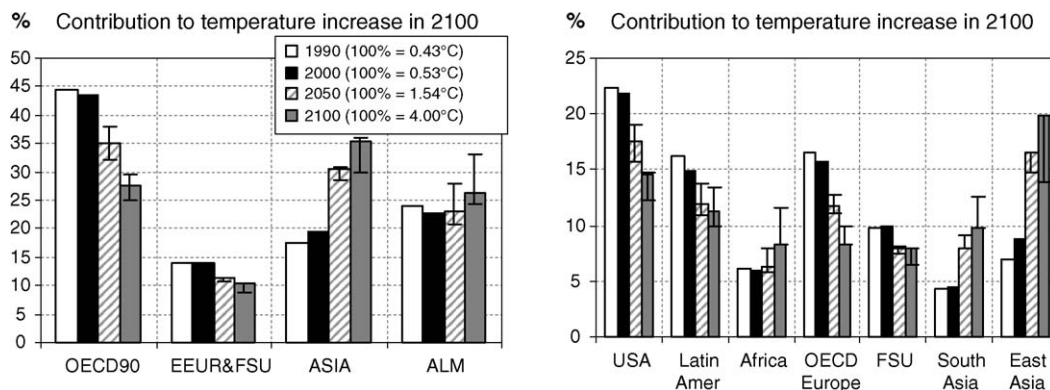


Fig. 9. Regional contributions to the global-mean surface temperature increase for the alternative end date cases in 2100 (including the reference case 2000; start date 1890; background scenario: IPCC SRES A2). The bars represent the range in results when the future emissions trajectories are based on the IPCC SRES A1, A2, B1 and B2 scenario for the ACCC model (den Elzen et al., 2002). Numbers given in parentheses in the legends show the magnitude of the warming that is subject to attribution. Source: RIVM-ACCC.

warming, and also discounts early effects. It therefore shifts the weight towards the effect of long-lived gases and towards most recent emissions. Fig. 10 depicts the impact of various evaluation dates (Table 1), using the default values for the attribution start date (1890) and end date (2000). With a

fixed attribution end date (2000) for an evaluation date far beyond 2000, the relative contribution for the OECD90 region rises, while contributions for the other regions drop. The major reason is related to the relatively small share of CH_4 emissions for OECD90 compared to other regions.

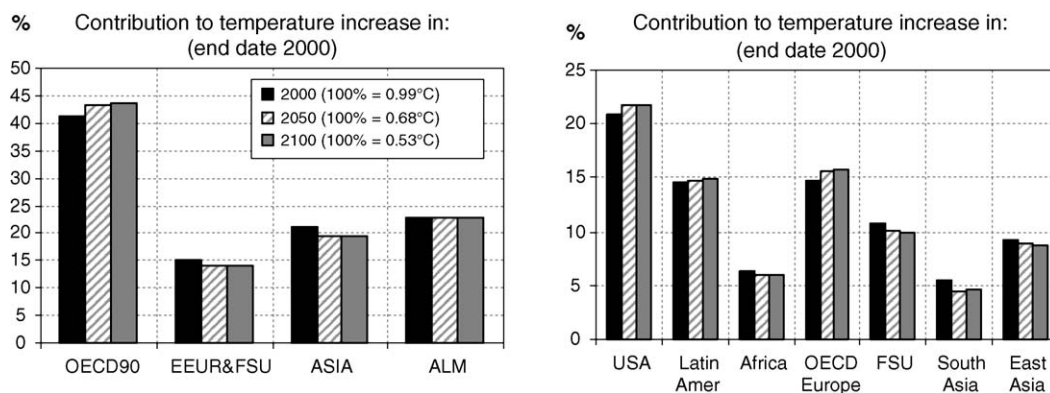


Fig. 10. Regional contributions to the global-mean surface temperature increase for the alternative evaluation-date cases (including the reference case 2000) (attribution period: start date–end date 1890–2000) (den Elzen et al., 2002). Numbers given in parentheses in the legends show the magnitude of the warming that is subject to attribution. Source: RIVM-ACCC.

Since CH_4 has a relatively short lifetime in the atmosphere, the large amount of forcing resulting from CH_4 emissions for non-OECD90 regions just before the attribution end date will dissipate quickly. Thus non-OECD90 contributions are lowered compared to OECD90 contributions as the evaluation time is shifted further into the future. Another reason explaining this is the large OECD90 share in historical CO_2 emissions. Historical emissions form a large part of the contribution to CO_2 concentration due to the slow responses of some components of the carbon cycle. Thus, the fraction of total contribution caused by historical emissions remaining in the atmosphere will fade away more slowly than the contribution from e.g. methane.

3.2.3. Attribution methods

The climate system is not a linear system. For example, the increase in radiative forcing per ppmv of CO_2 concentration decreases as atmospheric concentration increases, due to the saturation effect (Ramaswamy et al., 2001). At 300 ppmv CO_2 concentration, an additional ppmv causes 0.018 W/m^2 radiative forcing, while at twice the concentration, at 600 ppmv, the effect of an additional ppmv is only 0.009 W/m^2 , which is half of the effect at 300 ppmv. In this step of the cause effect chain, “early emissions” result in a bigger effect per ppmv than “late emissions”.

There are a number of different approaches that can be used for calculating regional contributions of global warming for non-linear models. Trudinger and Enting (2005) presented a detailed description and comparison of seven attribution methods and rated them against a set of criteria. The report of the MATCH meeting September 2003 (Höhne and Ullrich,

2003) also provides an inventory of methods. Choice of attribution method has both policy-related and scientific components. Considering only non-linearity in the radiative forcing step, today’s CO_2 emissions have a reduced impact on temperature due to ‘early’ emissions that remain in the atmosphere. Should this reduced impact be considered only for today’s emissions, or shared between all emissions remaining in the atmosphere? Non-linearities or feedbacks in other parts of the cause–effect chain can be of the opposite sense. The question of who is responsible for observed changes in such cases has no single correct scientific answer. Different attribution methods deal with the effect of the non-linearities differently, so choosing between the methods is partly a policy choice. On the other hand, some attribution methods have obvious difficulties, e.g. the results of one attribution method depend on the degree of disaggregation of the considered sources, and it could therefore be ruled out with scientific arguments.

Here we will compare three of the attribution methods: (1) the ‘normalised marginal’ method (equivalent to, yet more general than, the ‘proportional’ method); (2) the ‘normalised residual’ method and (3) the ‘time-sliced’ method, as those are most suitable and/or universally applicable. When discussing the methods, we will consider mainly the ACCC default case with only a non-linear radiative forcing model, but most of the discussion is also relevant for the more general case of non-linearities at other steps.

The *marginal method* calculates the sensitivity of radiative forcing ‘at the margin’. That is, the effect on radiative forcing of each unit of concentration is equal to the effect due to the last unit of concentration (Fig. 11a).

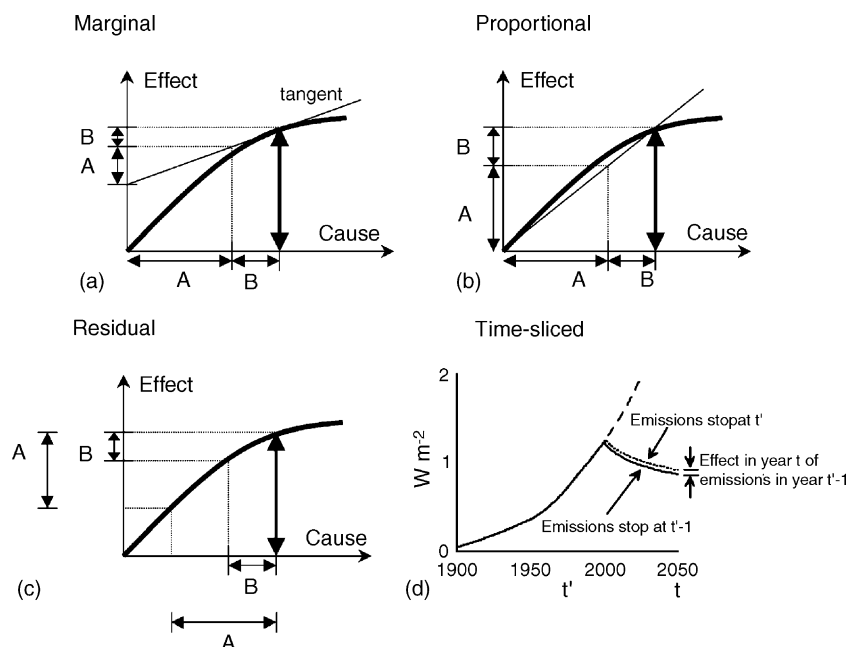


Fig. 11. Schematic diagrams of a non-linear relationship between cause and effect, illustrating attribution for regions A and B by the (a) marginal, (b) proportional or normalised marginal and (c) residual methods. (d) Example illustrating the time-sliced method for radiative forcing. The solid line has emissions following a reference scenario until $t' - 1$ then zero thereafter, while the dotted line has emissions following the reference scenario until t' then zero. The difference between these two curves is the effect on radiative forcing of emissions in year t' (Trudinger and Enting, 2005).

The sum of the regional components does not equal the global effect (because the sensitivity at the margin differs from the *average* sensitivity), but the results can be normalised so that the sum does match the global value.

The proportional method obtains the same results as the normalised marginal method but by a different approach. Radiative forcing is partitioned in proportion to the partitioning of concentration (Fig. 11b). The effect of each unit of concentration is equal to the average effect of all (anthropogenic) units of concentration (i.e. all units of concentration above the pre-industrial equilibrium level). The proportional method is straightforward for one-to-one functions, where the effect depends on the cause at the same point of time (e.g. the concentration to radiative forcing step). However, for many-to-one functions, like emissions to concentration, where the effect depends on the cause at a range of past times, the proportional method is not so straightforward. As the normalised marginal method is equivalent to proportional, but more general, we prefer this method.

The *residual method*, or ‘all-but-one’ method, compares the effect of leaving out the emissions of each region in turn. The radiative forcing due to one region is the difference between the total radiative forcing and the radiative forcing when the effect of that region is removed (Fig. 11c). The sum of the regional contributions does not match the global total, but this is not a problem as the results can be normalised. An important disadvantage of the method is that the results are not additive (i.e. $F_A + F_B \neq F_{A+B}$). Note that this is a different issue to the regional components not adding up to the global total, and can be explained by contrasting the residual and marginal methods, both of which have regional contributions that do not add up to the total. The marginal method is additive as it treats the effect of each unit of concentration (at a particular time) the same regardless of the size of the regions (all units are calculated with sensitivities at the margin). The residual method is not additive, as regions with lower emissions have sensitivities that are closer to the margin (lower radiative forcing per unit concentration) than regions with higher emissions, due to the nonlinearity. The fact that the results are not additive means that the effect due to a group of regions, such as the countries in the European Union, differs depending whether they are treated as a single unit or individual components. In addition, attribution of other countries also differs depending whether the European Union is treated as a single unit or individual countries. An advantage of the normalised residual method is that it is easy to implement and understand.

The *time-sliced method* (Enting and Law, 2002) determines the effect of emissions from each time, as if there were no subsequent emissions. For example, the effect of emissions in year t' on the radiative forcing at time t is the difference between two scenarios: one in which emissions of the gas follow the reference scenario to $t' - 1$ and are zero thereafter, and a second in which emissions of the gas follow a reference scenario through to year t' and then fall to zero (Fig. 11d). This

process is followed for each year of emissions to give the contribution of all emissions at all time. Thus, the effect of early emissions does not depend on later emissions. Regional contributions sum to the global total and do not require normalisation. A feature of this method is that attributing committed future warming due to emissions up to today does not depend on a future emissions trajectory.

Fig. 12 shows attribution of temperature increase in 2000 and 2100 with these three attribution methods for the CSIRO-ACCC model. The differences between methods are fairly small compared to the effects of many of the other choices already considered. In general, the results of the different attribution methods vary most for regions that differ most from the average in terms of early versus late emissions. Such differences may be more pronounced if emissions from individual countries are considered.

Other attribution methods have been used or discussed elsewhere in addition to the three methods presented above (e.g. Enting and Law, 2002; den Elzen et al., 2002; Andronova and Schlesinger, 2004) but they can be excluded on scientific grounds or because they are not applicable to radiative forcing (Trudinger and Enting, 2005). Of the three methods considered here, the normalised residual method is simple to implement, but has an important disadvantage that it is not additive and therefore could be ruled out on scientific grounds. The normalised marginal and time-sliced methods are harder to implement, but satisfied all of the criteria discussed by Trudinger and Enting (2005) (including being understandable, additive, add to give the global total, no paradoxical behaviour, and being applicable along the cause–effect chain for the general case of non-linearities at each steps). It is also easy to describe these two methods in terms of how they treat emissions from different times (normalised marginal treats each unit of the cause the same, while time-sliced treats units of the cause differently depending on the emissions they correspond to), and the choice between these methods would be a policy choice. The normalised residual method cannot be compared to the other two methods in this way, as the results will differ with disaggregation of the emissions into regions. It should be noted that the time-sliced method might not be practical to implement for some complex, time-consuming models, as many iterations are required.

Little work has been done on testing the attribution methods for more complex climate models that include several non-linearities along the cause effect chain, non-linear climate-impact functions multiple interdependent gases, climate-carbon feedbacks and/or negative emissions (sequestration). This is an area in need of further work. In Section 3.3.3, as a first attempt, we will explore the impact of more simple feedbacks as included in the UCL-JCM model.

3.2.4. Greenhouse gas mix

The UNFCCC states that policies and measures to address human-induced climate change should be comprehensive and cover all relevant sources, sinks and reservoirs

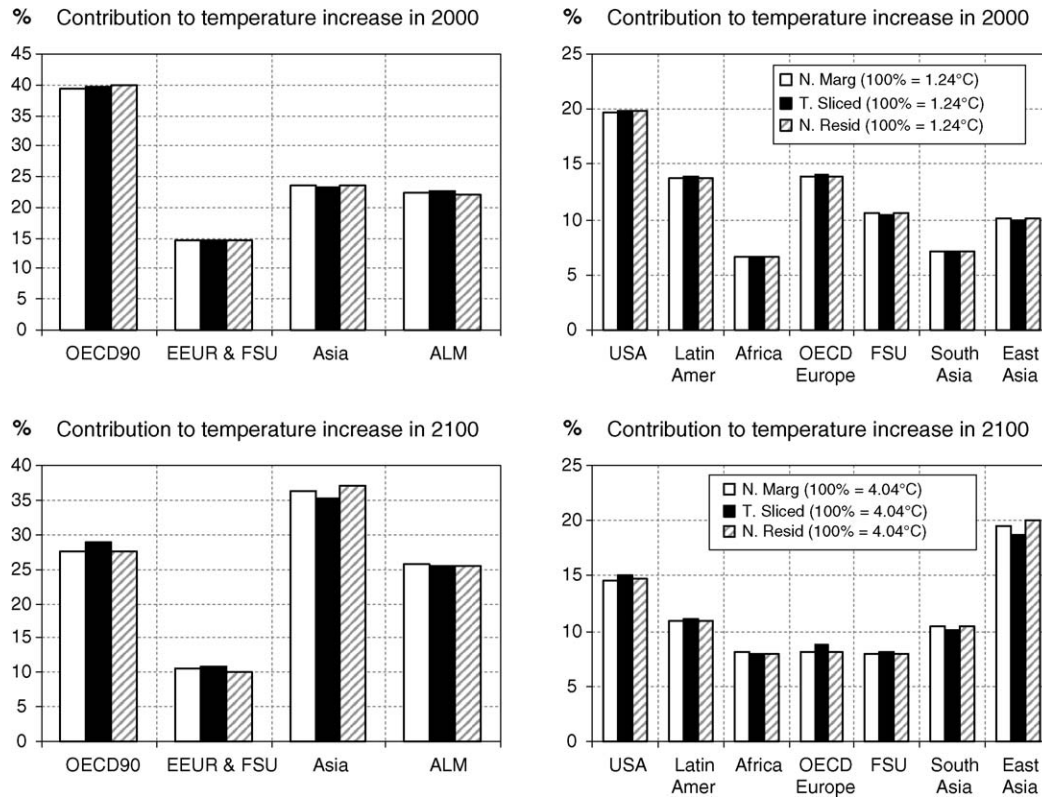


Fig. 12. Regional contributions to the global-mean surface temperature increase for different non-linear attribution methodologies (for the evaluation dates 2000 and 2100 and the attribution period 1890–2000). Source: CSIRO-ACCC.

of GHGs (Art. 3.3). In the Kyoto Protocol this principle is made operative as the aggregate CO₂ equivalent emissions (calculated by GWP₁₀₀) of six GHGs or groups of GHGs (Art. 3.1, Annex A): CO₂, CH₄, N₂O, HFCs, PFCs, SF₆ (hereafter 'Kyoto gases'). Since the different regions/countries show different historical mixes of emissions of these GHGs, the number of gases included in the attribution will affect the calculated contributions. Although it may be argued that an obvious choice would be to include all the Kyoto gases, we have tested the effects of including various numbers of gases. We have used the CICERO-SCM and the normalised marginal attribution method.

Ideally, an attribution analysis should include all man-made forcing agents and not only those gases that are included in climate policies. Species that cause significant radiative forcing, but *not* included in attributions are the ozone depleting substances, such as CFCs and HCFCs that cause radiative forcing directly (warming) due to their own radiative properties, and indirectly by reducing stratospheric ozone (cooling). Aerosols such as fossil fuel organic carbon (cooling) and fossil fuel black carbon (warming) as well as aerosols from biomass burning (cooling) are candidates for more detailed and sophisticated attribution studies. Aviation induced forcings via contrails and cirrus formation (both warming) could in principle also be included although it may be difficult to allocate these emissions to nations since this is an international activity.

Here we narrow our analysis down to the Kyoto gases, as well as precursors of tropospheric ozone. Thus, the attribution calculations are performed for the following cases of gas mixes (i.e. number of gases included in the attribution): (1) fossil-fuel CO₂; (2) Total anthropogenic CO₂ (i.e. fossil-fuel and land use changes); (3) Total CO₂, CH₄, N₂O (default); (4) Kyoto gases; and (5) Kyoto gases and NO_x, VOC and CO. The calculations include the indirect forcing from CH₄ via effects on stratospheric H₂O and tropospheric O₃, and are thus consistent with the IPCC GWPs. Fig. 13 shows the calculated contributions for these cases. According to these results there are two main shifts in the effects of gas mix. The strongest effect is going from only fossil fuel CO₂ emissions to all anthropogenic CO₂ emissions. This reduces the OECD90 share from 59 to 44%, and increases the contributions of ASIA and ALM by approximately 5 and 15 percentage points, respectively.

The next shift is the inclusion of N₂O and CH₄; which further reduces the OECD90 contribution to 38%, while the contribution from ASIA increase by 8 percentage points. The effect of including the rest of the Kyoto gases is negligible for the contributions in 2000. Similar conclusions were found by den Elzen and Schaeffer (2002).

Tropospheric ozone gives a significant contribution to man-made warming (next after CH₄). This gas is partly covered by the Kyoto Protocol via the indirect effect on O₃ included in the GWP for CH₄. But CO, VOC and NO_x also

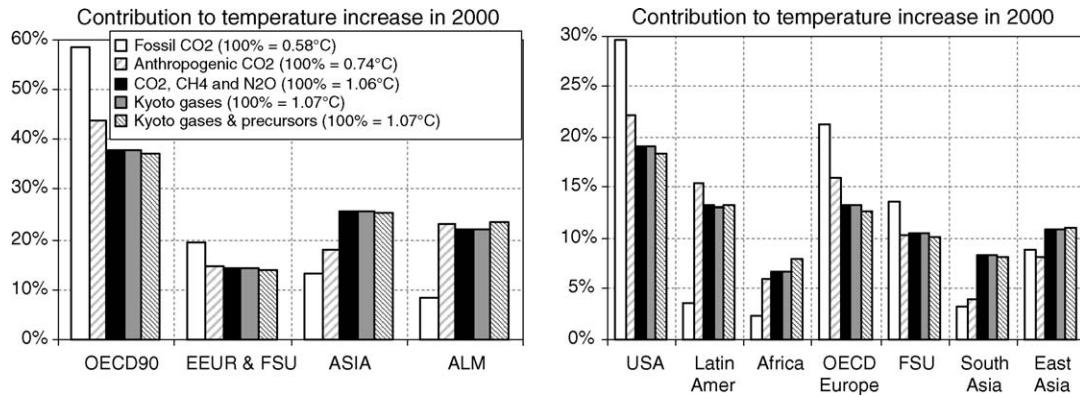


Fig. 13. Calculated contributions to the global-mean surface temperature increase for different numbers of gases included in the attribution (for the evaluation date 2000 and the attribution period 1890–2000). Numbers given in parentheses in the legends show the magnitude of the warming that is subject to attribution. Source: CICERO-SCM.

affect tropospheric O₃. Furthermore, CO and VOC increase the lifetime of CH₄, while NO_x, on the other hand, reduces the levels of CH₄. Including the emissions of these gases in the attribution calculations reduce the contribution for all regions except ALM. The magnitude of warming that is subject to attribution, however, remains practically unchanged.

Using a time gap between attribution end date and evaluation date allows for capturing the delayed response of the climate system. During this period the effect of some short-lived gases may have died out. Some of the gases studied above have significantly shorter adjustment times than CO₂ and N₂O. Methane's adjustment time is 12 years, while for tropospheric ozone it is a few months. Using 2050 as the evaluation year gives broadly the same pattern, with large effect of including CO₂ from land use change and a significant effect of including CH₄, but the differences between the cases become somewhat smaller.

Fig. 14 shows the same cases, but now with an attribution end and evaluation date of 2100 (using the SRES-A2 scenario). The effects of changes in the number of gases attributed are less pronounced in a longer time perspective, mainly because CO₂ becomes increasingly important as the main forcing agent in future scenarios.

In these attribution calculations it is assumed that the effects of NO_x on O₃ are independent of geographical location. The difficulties in calculating the climate effects of short-lived gases like NO_x (and SO₂) is not only restricted to attribution calculations; these difficulties are also present in scenario calculations (e.g. in IPCC-TAR) based on simple climate models.

3.2.5. Aerosols

Sulphur dioxide (SO₂) is a short-lived gas with strong direct and indirect forcing of negative sign (cooling). Accounting for these effects in calculations allows a more realistic representation of the global temperature. This gas is so far not included in any official climate policies but is included in regional agreements aimed at reducing acidification and improving air quality. Attributing effects

from SO₂ to sources will reduce the net forcing and absolute contributions to warming for all emitters of this gas. In contrast to the important GHGs, the negative forcing from SO₂ can be regarded as instantaneous. This gas was not included in the Brazilian proposal, but is included here in order to study how a “net forcing perspective” would differ from the “warming perspective” that is usually applied, recognising that there is an ongoing discussion whether such “net forcing perspective” could be applied (Rypdal et al., 2005). Whilst it would seem obvious to some that, in apportioning responsibility for climate change, cooling aerosols should not subtract from the positive forcing of GHGs, it is nevertheless instructive to look at how their inclusion changes attributions. (Black carbon aerosols cause warming and are not included in this attribution.)

For attribution start and end dates of 1890 and 2000, respectively, and an evaluation year of 2000 (default choices) we find that the contributions from OECD90 and ALM increase when SO₂ is included and attributed, while

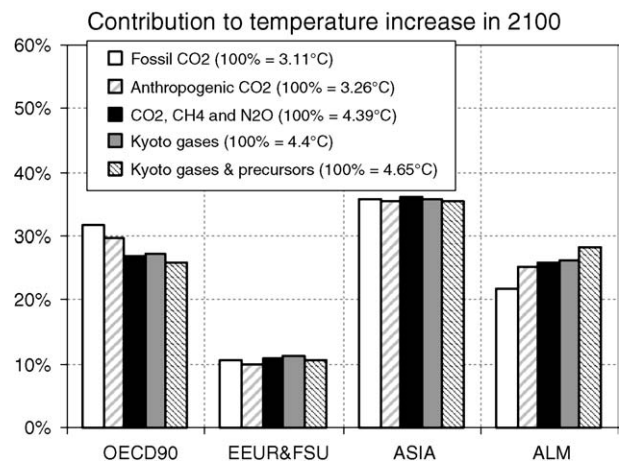


Fig. 14. Calculated contributions to the global-mean surface temperature increase for different numbers of gases included in the attribution (for the evaluation date 2100 and the attribution period 1890–2100; background scenario: SRES A2). Source: CICERO-SCM.

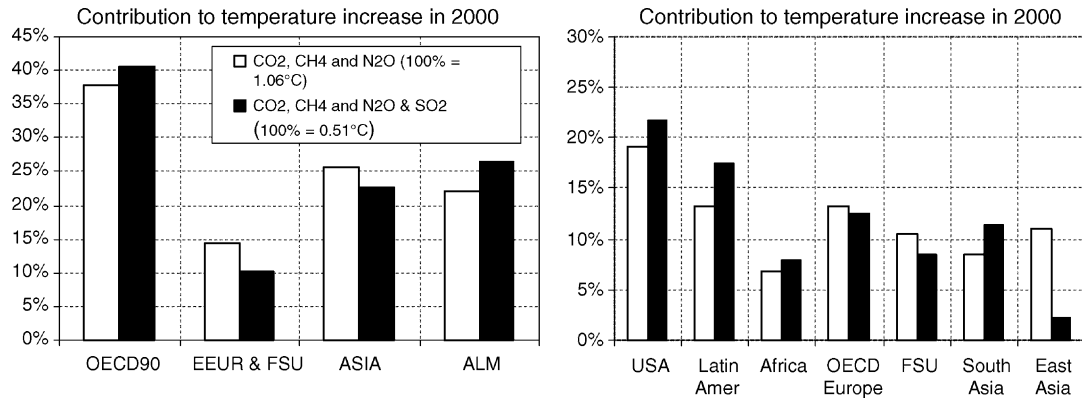


Fig. 15. Calculated contributions with and without SO₂ included in the attribution (for the evaluation date 2000 and the attribution period 1890–2000). Source: CICERO-SCM.

the contributions from ASIA and EEUR&FSU decrease (Fig. 15). While all regions have reduced their absolute contributions to global warming, ASIA and EEUR&FSU will have reduced their contributions relatively more than others and will therefore end up with a smaller share. When there are large differences between the adjustment times of the gases included in the calculations, the timing of the emissions becomes important. Due to the instantaneous nature of forcing from SO₂, emissions close to the evaluation year (2000 in our case) will have a large effect on the attribution. The effect of SO₂ disappears when there is a gap between attribution end year and evaluation year. For 2050 as evaluation date the relative contributions are almost identical to the case without SO₂.

3.3. Scientific choices

In this section, some scientific choices related to the contributions to climate change are assessed. It is the first comprehensive assessment of the sensitivity to various scientific uncertainties, and further work is needed to test assumptions. Here, we focus on examples of scientific choices, including different historical emissions datasets, climate models, carbon cycle models, representations and parameterizations of atmospheric chemistry and climate feedbacks. These choices representing a range of scientific uncertainties of some studies, forming a part of the full uncertainty range, but this is not a comprehensive spanning of uncertainty ranges.

3.3.1. Different historical emissions datasets

There is an inherent uncertainty in the determination of historical emissions per country due to lack of reliable statistics or complete absence of both activity data and emission factors, particularly prior to 1950. Most reliable emission estimates are available for fossil fuel related CO₂ emissions, but even here the energy content per unit of mass, e.g. coal, is not well known for all countries, resulting in additional uncertainty. There are a number of global emission datasets available for CO₂ emissions from fossil

fuel use and industrial processes on a country-by-country or regional basis, as implemented here at the level of the 13 world regions, i.e. CDIAC-ORNL database (1765–2000) (Andres et al., 1998) and the EDGAR database (1890–1995) (Van Aardenne et al., 2001). It is important to point out that the EDGAR database has been scaled with the IPCC scenarios.⁹

For the CO₂ emissions from land-use changes, there are more substantial differences between emission estimates. We tested the sensitivity to using three alternative datasets: Houghton (1999), the EDGAR database and new estimates from IVIG-HYDE (de Campos et al., 2005), which uses the HYDE database for the historical land use changes (Klein Goldewijk, 2001).

For the historical emissions of the major non-CO₂ GHGs, only the EDGAR database is available. These data on CH₄ and N₂O emissions are very uncertain, which is partly due to the uncertainty in non-CO₂ emission factors. While the uncertainty in emission estimates tends to increase when going back in time, their contribution to concentrations and final temperature increase levels, becomes increasingly less due to both lower activity levels and the atmospheric decay of past emissions (see den Elzen et al., 1999).

Fig. 16 shows that the impact of choosing the CDIAC instead of the EDGAR dataset for the historical CO₂ emissions from fossil fuels and cement production is limited. The impact of choosing the land use CO₂ emissions from the dataset of Houghton or IVIG-HYDE instead of EDGAR clearly changes the outcomes. Choosing the Houghton's land use emissions increases the contributions of Asia and

⁹ This is based on revised data from EDGAR, with a fraction of 30% instead of 10% for the biofuel combustion emissions, as this is a rather uncertain factor. The revised EDGAR 1990 emissions value is now 0.65 GtC/year, which is more in line with 1.0 GtC/year of the IPCC SRES emissions scenarios. The 1990 emissions value of the Houghton database is much higher, more than 2 GtC/year. Also the historical (1890–1995) anthropogenic N₂O emissions have been scaled with a constant regional factor so that the resulting 1995 emissions for the four IPCC-SRES regions match with the 1995 values of the IPCC SRES scenarios (Nakicenovic et al., 2000).

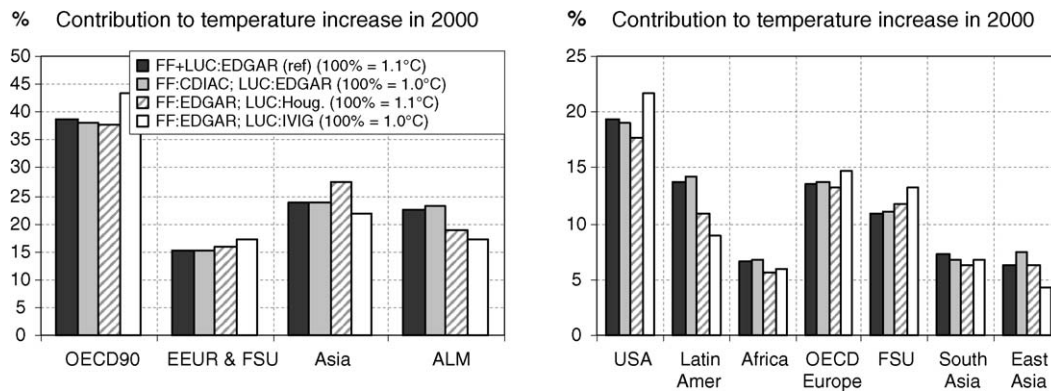


Fig. 16. Regional contributions to the global-mean surface temperature increase in 2000 for the EDGAR database (all GHGs) and alternative databases (attribution period 1890–2000). Legend: FF: (fossil) CO₂ emissions and LUC: land use CO₂ emissions. The historical CH₄ and N₂O emissions are based on the EDGAR database for all cases. Source: IVIG-ACCC.

decreases the contribution of Latin America. Choosing the IVIG-HYDE's land use emissions mainly decreases the non-Annex I contributions, and thus increases the Annex I contributions, as the land use emissions of IVIG-HYDE are rather low for Latin America and Africa, and also Asia¹⁰, compared to the Houghton and EDGAR estimates. From different dataset combinations of the second graph in Fig. 16, we can conclude that the variations among the land use change emissions estimates affects the contributions, in particular for the non-Annex I regions, where the land use emission are considerable compared to their fossil fuel emissions.

To conclude, effort is needed to improve the methodology and datasets for calculating net emissions from land-use change, since various datasets show large differences in the regional estimates, even in recent decades. These differences have large impacts on the calculated contributions to global warming.

3.3.2. Global climate models

The transient response of atmosphere-ocean climate models to a particular anthropogenic forcing is strongly dependent on the climate sensitivity and the effectiveness of the models' oceans at taking up heat (Raper et al., 2002). The uncertainties of these quantities combine to cause the uncertainty in the IRFs used in the ACCC models. den Elzen and Schaeffer (2002) have analysed this by assessing the influence of global temperature IRFs, based on climate simulation experiments with nine GCMs. They also looked at the impact on the regional attribution calculations, concluding that different IRFs have limited impact on the relative contributions, at least in the first half of the 21st century. Here, we have redone the calculations for the

default case and found similar findings. For all regions the differences in attribution for the nine GCMs is less than 1 percentage point. There is some evidence that the climate sensitivity may change over time as the strength of feedbacks within the climate system change (Senior and Mitchell, 2000) and it is plausible that changes in ocean circulation will alter the rate of ocean heat uptake. These additional effects cannot easily be addressed with the IRF models used here. However, it seems unlikely that these two factors will result in significant differences in attribution.

3.3.3. Carbon models and climate-carbon feedbacks

The Java Climate Model (JCM) was used to explore the effect of varying the carbon cycle model and of climate-carbon feedbacks. The legend of Fig. 17 lists the model variants that were explored, gradually increasing the complexity of the carbon cycle model and adding feedbacks. This set of variants was chosen merely to test sensitivity to model parameters, we acknowledge that a more balanced, coherent analysis might consider the probability of each combination depending on the fit to historical measurements. For all variants, the attribution period is from 1900 to 2100 and the evaluation date 2100 (in contrast to ACCC default 2000)—this is to enable exploration of feedback effects, which only become large at higher CO₂ and/or temperature levels. In most variants (all except 1 and 8) all gases (including F-gases and ozone, carbon and sulphate aerosols) and natural forcings (solar/volcano) were included, to provide a better fit to the observed temperature record and hence a better basis for calculating climate-carbon feedbacks.

The difference in *relative* attribution between variants 1–4 is solely due to the carbon cycle, since the additional forcings from unattributed gases do not make any difference before temperature feedbacks are introduced. As the ACCC carbon cycle model is a linear approximation to the Bern carbon cycle model, the main change between variants 1 and 2 is the non-linear (logarithmic) carbon fertilisation effect. In variant 3 non-linear ocean carbonate chemistry is

¹⁰ The IVIG-HYDE land use CO₂ emissions of the developing countries become almost zero in 1990s, which is very low compared to estimates of many other studies and the IPCC-TAR range of 1.6 ± 1.0 GtC/yr, therefore here the regional emissions after 1980 were kept constant until 2000 for the default calculations.

introduced, and in variant 4 this is also affected by ocean temperature (which changes the equilibrium constants and solubility, so the attribution of the extra sea-air flux is traced from both water $p\text{CO}_2$ and temperature). Variant 5 shows the UCL-JCM default (as used for Figs. 3 and 4). This is like variant 4 but with variable lifetimes for CH_4 and N_2O . Fixed (ACCC) lifetimes were used in other variants in order to focus on the carbon cycle changes. In variant 6 an additional feedback effect of temperature affecting soil respiration was added, adapting the simple “ Q_{10} ” formula of Jones et al. (2003). In variant 7, the climate sensitivity was increased to 4.5 (compared to 3.0 for HadCM3), in order to test the effect on the climate-carbon feedbacks. As expected, the increased sensitivity substantially amplifies the effects of the feedbacks (whilst a control without feedbacks showed little effect of sensitivity on attribution). In variant 8 only the three ACCC gases are included in calculation of the temperature, and solar variability and volcanoes are also removed, but the effect on the relative attribution of CO_2 , through climate-carbon feedbacks, is very small. Note, as this simple model is not spatially resolved it cannot capture regional effects such as forest dieback due to changing precipitation patterns, as observed in some GCM projections, nevertheless it provides a test of sensitivity of relative attribution to climate-carbon feedbacks. All of the feedbacks increase the atmospheric CO_2 concentrations, and substantially increase the absolute temperature changes, which range between 3.1 and 6.9 °C in 2100 for the variants shown in Fig. 17 (note also

numbers in figure legend). However, the figure shows that their effect on relative attribution is only small, in general increasing the contribution of earlier emitters. Even for the most extreme case (variant 7) the relative change in contribution is at maximum 4% of the default value.

3.3.4. Tropospheric oxidation capacity

Most of the Kyoto gases are not chemically active in the troposphere, which means that their lifetimes are not sensitive to changes in chemical processes there. The important exceptions are the gases that have reaction with the hydroxyl radical (OH) as their main sink; i.e. CH_4 and HFCs. The treatment of the OH controlling processes is therefore crucial for the modelling of past and future concentrations of these GHGs. OH itself is controlled by several gases, mainly CH_4 , CO, VOC and NO_x , in addition to UV radiation and water vapour. CH_4 emissions will reduce OH levels and increase its own adjustment time thereby causing an additional increase in concentrations. CO and VOC have a similar effect on OH and CH_4 , while NO_x , on the other hand, increases the levels of OH, thereby reducing the CH_4 levels (e.g. Fuglestad et al., 1996). These effects need to be parameterised in simple gas cycle or climate models. den Elzen et al. (2002) tested the effect of changes in adjustment time of CH_4 and found that although the choice between constant and variable adjustment time is important for the absolute methane levels, it has only a negligible effect on the relative contributions. The effect of

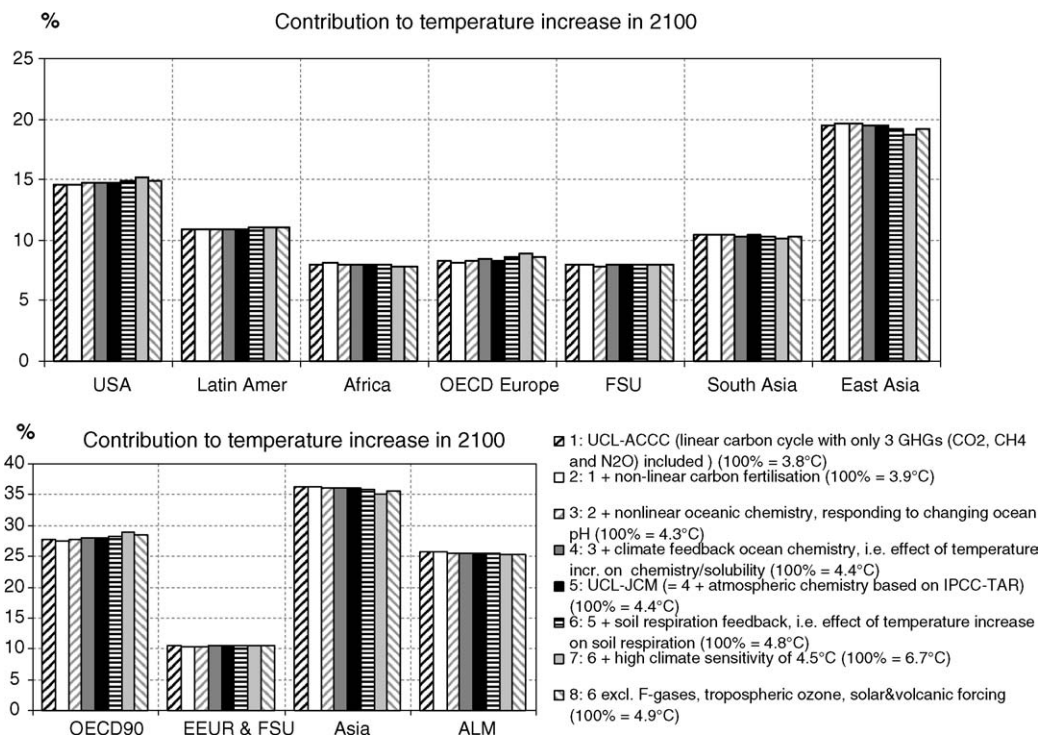


Fig. 17. Contribution to temperature increase as a function of different carbon/climate models parameter settings. Attribution period 1890–2100, evaluation date 2100. Note: the 100% numbers in the legend is based on the sum of all regions, excluding the non-unattributed forcings. Including these unattributed forcings would lead to 100% values (in °C) of: 1: 3.2; 2: 4.2; 3: 4.6; 4: 4.7; 5: 4.9; 6: 5.1; 7: 6.9; 8: 3.9. Source: UCL-ACCC/UCL-JCM.

constant CH₄ lifetime versus the TAR formulation on attribution was also tested with the CICERO-SCM and shifts up to approximately 1 percentage point were found for the default case with four regions. The effect (via CH₄) of including NO_x, CO and VOC among the attributed gases was of similar magnitude.

3.4. Summary of the importance of policy-related choices and scientific choices

To prioritise the different policy and scientific choices in terms of impact on the attribution calculations, we have summarised the results of our analyses in Table 4. Here, we show the relative contributions for each region when different options on attribution start and end dates, parameter settings, model approaches, etc are implemented. Policy-related choices are on the left and the scientific choices on the right. Cases where the altered parameter setting leads to an *increase* in relative contribution of more than 10% (of the default value) are shaded in dark grey, and cases where the altered parameter setting leads to a *decrease* in relative contribution of more than 10% (of the default value) are shaded in light grey. The different cases are calculated with different models, which have slightly different results for the default case. Therefore the results should be compared only within one model.

For example, the relative contribution from Canada using the CICERO-SCM changes from 1.5% for the default to 2.2% when only fossil CO₂ emissions are taken into account; i.e. an increase larger than 10% in relative contribution (and thus shaded in dark grey).

For the IPCC regions, the strongest influence on contributions is found for the policy-related choices of attribution start date and the choice of including all gases or only fossil CO₂, or aerosols. Also the change to the indicator “ocean heat content” is significant. From the scientific choices only the choice of the dataset for historical land use emissions has a significant effect. All other factors change contributions of all regions less than 10%. The impact of these main choices on the relative contributions are also summarised at the level of the 4 regions in Fig. 18, where the numbers are given as deviation from the default results.

The choice of the attribution method has relatively low influence on the calculated contributions. Also the choice of the climate model, feedbacks such as carbon fertilisation or climate feedbacks or even an extreme setting such as a climate sensitivity of 4.5 °C have no significant effect on the relative contributions. The effects are more pronounced if applied later in the century as non-linearities are more relevant, but still less than the magnitude of the policy-related choices.

For some factors, the results of the four regions do not change significantly, but the results do change significantly for the 13 regions. For example the move from the indicator temperature increase to weighted concentrations is of minor influence on the 4 regions level, but of major influence for

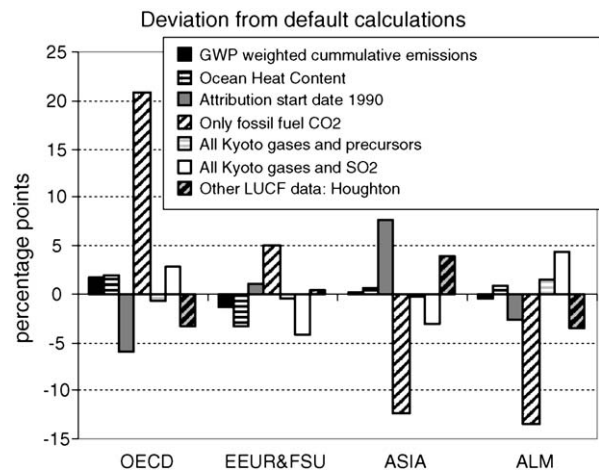


Fig. 18. Summary of impact of the main policy-related and scientific choices on relative contributions in terms of deviation from default calculations (percentage points).

Middle East, South-Asia region and Japan. This is an indication that future analysis has to be performed on further disaggregated datasets to capture the particularities of individual countries.

3.5. Combining methodological choices

Combining various options does not necessarily lead to a total of linearly adding the changes in contributions as seen in from Table 4. In addition, some combinations of options that modify contributions for a specific region might, of course, be impossible or meaningless.

When testing combinations of the choices we observe several general patterns:

- The choice of the attribution start date and the choice of including land-use CO₂ as well as including CH₄ and N₂O always have a large influence, regardless of all other settings.
- Some indicators are more sensitive to other settings than other indicators, e.g. GWP weighted cumulative emissions, weighted concentrations and integrated temperature increase incorporate future effects, and therefore the concept of an evaluation date is not relevant or already included in the time horizon of the GWP. Indicators that give less weight to far distant emissions (radiative forcing, weighted concentrations) are less sensitive to uncertain past emissions, while ocean heat uptake strongly relies on far distant emissions.
- The further the time horizon is moved to the future (using a later evaluation date, or using an indicator that integrates into the future), the more pronounced become the non-linearities and feedbacks in the climate system. Hence, the influence of the attribution method and the representation of the climate system become more important. For the considered regions, we find, however, a maximum change of 4 percentage points (compared to default) for extreme

Table 4

Summary of relative contributions of regions using the default case and variations in policy-related and scientific choices

Region	Indicator ECOFYS-ACCC					Timeframe RIVM - ACCC			Attribution CSIRO - ACCC		Greenhouse gas mixture CICERO-SCM					Emission data IVIG-ACCC		Feedback JCM-SCM	
	Default (temperature increase)	GWP weighted cumulative emissions	Weighted concentrations	Integrated Temperature increase	Ocean Heat Content	Default: Attribution start date 1890	Attribution start date 1990	Evaluation date 2100	Default: Normalized marginal	Time sliced	Default: all CO ₂ , CH ₄ , N ₂ O	Only fossil fuel CO ₂	Default with constant CH ₄ lifetime	All Kyoto gases and precursors	All Kyoto gases and SO ₂	Default: EDGAR	Other LUCF data: Houghton	Default: ACCC simplest	Variant 7 (sect. 3.3.3): UCL-JCM
Canada	1.6	1.6	1.7	1.6	1.4	1.7	1.8	1.7	1.6	1.6	1.5	2.2	1.6	1.8	1.4	1.6	2.2	1.6	1.6
USA	19.8	20.5	20.4	20.9	21.1	20.8	17.5	21.8	19.7	19.9	19.1	29.6	19.4	18.4	21.6	19.4	17.7	19.8	20.0
Latin America	13.7	13.7	13.3	14.2	15.4	14.5	10.0	14.8	13.7	13.9	13.2	3.7	13.4	13.2	17.5	13.8	11.0	13.7	14.0
Africa	6.5	6.3	6.2	6.2	6.6	6.3	6.5	6.0	6.6	6.6	6.8	2.4	6.7	7.9	8.0	6.7	5.6	6.6	6.6
OECD Europe	13.8	14.7	14.5	14.9	15.2	14.7	11.0	15.8	13.9	14.0	13.2	21.3	13.6	12.8	12.5	13.6	13.2	13.9	14.2
East Europe	4.1	3.9	4.0	4.1	3.6	4.2	3.4	4.2	4.0	4.0	3.9	5.8	3.9	3.7	1.8	4.2	4.0	4.0	3.9
FSU	10.8	9.6	10.3	10.1	7.9	10.7	12.5	9.9	10.7	10.5	10.5	13.7	10.4	10.2	8.4	11.0	11.7	10.3	9.9
Middle East	2.1	1.9	2.4	2.1	1.2	2.0	3.7	2.0	2.1	2.0	2.0	2.5	2.0	2.4	0.9	2.1	2.4	2.1	1.9
South Asia (incl. India)	7.0	7.3	5.8	5.6	8.7	5.5	7.4	4.5	7.1	7.1	8.5	3.3	8.0	8.2	11.4	7.3	6.3	7.2	7.6
East Asia (incl. China)	10.2	10.1	10.7	9.7	8.9	9.3	15.2	8.8	10.1	10.0	11.0	8.9	10.6	11.0	2.3	10.2	15.1	10.3	9.9
South-East Asia	6.3	6.2	6.0	6.1	6.6	6.2	6.0	6.0	6.2	6.3	6.3	1.2	6.3	6.3	9.1	6.4	6.3	6.3	6.3
Oceania	1.5	1.5	1.6	1.4	1.5	1.3	1.6	1.2	1.7	1.7	1.8	1.2	1.7	1.7	2.2	1.5	1.8	1.7	1.7
Japan	2.6	2.6	3.0	2.9	1.9	2.9	3.5	3.1	2.5	2.5	2.3	4.3	2.4	2.3	2.9	2.5	2.8	2.5	2.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
OECD	39.3	40.9	41.3	41.8	41.1	41.2	35.3	43.6	39.5	39.6	37.8	58.6	38.6	37.0	40.7	38.3	37.7	39.5	39.9
EEUR&FSU	14.8	13.5	14.4	14.2	11.6	14.9	15.9	14.1	14.7	14.5	14.4	19.5	14.4	13.9	10.2	15.3	15.7	14.3	13.8
ASIA	23.5	23.6	22.5	21.4	24.2	21.0	28.6	19.4	23.5	23.3	25.8	13.4	25.0	25.6	22.7	23.8	27.6	23.8	23.9
ALM	22.4	21.9	21.9	22.5	23.2	22.8	20.1	22.9	22.4	22.5	22.0	8.5	22.1	23.5	26.4	22.5	19.0	22.4	22.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
100% =	1.2 °C	160.4 yWm ⁻²	67.4 yWm ⁻²	84.0 °C _y	3.8E+09 J/m ²	0.99 °C	0.21 °C	0.53 °C	1.24 °C	1.24 °C	1.06 °C	0.58 °C	1.22 °C	1.07 °C	0.51 °C	1.06 °C	1.12 °C	0.52 °C	1.12 °C

XX = more than 10% higher than default; XX = more than 10% lower than default.

XX is contribution (%).

settings in 2100, which is still lower than the influence of the policy-related choices.

This analysis only compares the results of different policy-related and scientific choices. A full analysis of the overall uncertainty is left for further work.

4. Summary and conclusions

This paper evaluates the influence of different policy-related and scientific choices on the regional contribution to climate change. We generated and compared results of several simple climate models of varying complexity. For the default calculations, we found that the average calculated contributions to the global mean surface temperature increase in 2000 are about 40% (37.8–41.2%) from OECD, 14% (13.2–15.0) from Eastern Europe and Former Soviet Union (EEUR&FSU), 24% (21.0–25.8) (from Asia (ASIA) and 22% (21.5–22.8) from Africa & Latin America (ALM). It is not a full assessment of the uncertainty range. Here, we summarise the conclusions of the study of main choices and uncertainties.

Indicators—Neither the UNFCCC nor the Kyoto Protocol specify exactly which aspects of climate change are of most concern (climate parameter, rate or level of change, etc.). Thus, the choice of the indicator for contributions to climate change cannot be based on a formulated targeted policy or common conception of what is a main concern.

Two main factors influence the difference in the contributions to climate change using the different indicators: (a) whether gases were emitted ‘early’ versus ‘late’ and (b) the share of emissions of short-lived compared to long-lived gases. Backward discounting indicators give low weight to early emissions. Indicators that are not forward looking give high weight to short lived gases.

There is no obvious preferred choice of indicator of climate change. Temperature increase and ocean heat content, evaluated at the time emissions end, do not take into account the delay between radiative forcing, temperature change and heating of the ocean and therefore discount most recent emissions. On the other hand, the indicators temperature increase and sea level rise have the advantage of being understandable for policymakers and stakeholders, and the possibility to be measurable by instruments. It may be desirable to use these indicators only with an evaluation date later than the attribution end date.

If it is desired that the indicator is ‘backward discounting’ and ‘forward looking’, then ‘weighted concentrations’ or ‘integrated temperatures’ could also be considered. If ‘backward discounting’ is not desired, then GWP-weighted cumulative emissions would be an option, which is simple and approximately represents the integrated impact on temperature. But choosing the right indicator is ultimately a political choice that also depends on the use to which the results will be put.

Timeframes—We have also shown the methodological choices of time horizons to have a large impact on the contributions. Choosing an early attribution start date (1765 instead of 1890) increases contributions of regions that started emitting early. The opposite happens when choosing a later attribution start date (1990 instead of 1890) for historical emissions, i.e. it decreases the contributions of regions that started emitting early, such as the OECD countries by 6 percentage points, whereas it increases the share of late emitters such as Asia by 8 percentage points (see also Fig. 18). This also happens for a late emission end date, it increases the contribution of late emitters, e.g. non-Annex I, giving more weight to their projected larger shares in 21st century emissions.

For those indicators that are not ‘forward looking’ (radiative forcing, temperature increase and sea level rise), a time gap between attribution end and evaluation dates enables delayed, but inevitable, effects to be taken into account. It also discounts those effects that decay fast. It therefore shifts the weight towards long-lived gases and towards most recent emissions.

Attribution methods—The method used to attribute non-linear effects to the different regions has a minor effect on the results. We compared three attribution methods. The marginal method treats each unit of concentration of a gas in the atmosphere the same, and determines sensitivities ‘at the margin’. The time-sliced method treats each unit of concentration differently, depending on when it was emitted, with the effect of emissions from each time determined as if there were no subsequent emissions. The differences between these two methods represent a policy choice on how to decide who is responsible for observed changes. The residual (‘all-but-one’) method compares the effect of leaving out the emissions of each region in turn. The residual method has an important disadvantage that the results are not additive, and this is a scientific reason for not using this method.

Differences between results for four regions for the various attribution methods are typically 1%, and are greatest for regions whose emission time history varies most from the average in terms of early versus late emissions. The differences are small, but further analysis has to be undertaken to see if this is also true for finer regional resolution and use in more sophisticated models.

Number of source gases attributed—The calculations showed that there are two main shifts in the calculated contributions to temperature increase when the number of gases included is changed. The most important is the inclusion of CO₂ emissions from land use change in addition to CO₂ from fossil fuel emissions. Now, including only the fossil CO₂ emissions instead of the anthropogenic CO₂ (fossil and land-use change), N₂O and CH₄ emissions (default case) affects the attributions significantly; the OECD90 and EEUR&FSU shares are increased by 21 and 5 percentage points, while ALM and ASIA shares decrease by 12 and 14 percentage points each (see Fig. 18). The effect of including the remaining Kyoto gases SF₆, HFC and PFCs is negligible.

Inclusion of the non-Kyoto ozone precursors has a small but discernable effect; slightly increasing the contribution from ALM. In general, the more gases included, the lower are the contributions from the industrialised countries, but the effect is less pronounced on longer time scales. Inclusion of SO₂ emissions, which has a cooling effect, reduces the contributions from ASIA (3 percentage points) and EEUR&FSU (4 percentage points), but the effect disappears when there is a gap between attribution end date and evaluation date due to the short lifetime of SO₂ (Fig. 18).

Datasets—It is found that the differences between historical emissions of various datasets are significant, in particular due to the large uncertainty in the CO₂ emissions from land-use change (see Fig. 18) and the anthropogenic emissions of CH₄ and N₂O, but are smaller than the effect of many of the other choices already considered. This result is obtained for groups of countries, but may differ if individual countries are considered. Moreover, the analyses also indicated a rather rapid decrease with time in the influence of uncertainties in historical emission estimates due to both the dominating effect of the fossil fuel CO₂ emissions in the overall GHG emissions and the atmospheric decay of past emissions.

Carbon-climate feedbacks—We tested various parameters of a coupled carbon-climate model, including carbon fertilisation, non-linear ocean chemistry, temperature feedback on chemistry and soil respiration, and high climate sensitivity. While the range in absolute temperature for the different scenarios may be significant, the relative change in contribution is at maximum 4% (of the default value) for the most extreme case.

Concluding, results for relative contributions to climate are found to be quite robust across a range of various simple models and scientific choices. Policy-related choices such as time period of emissions, climate change indicator and gas mix, generally have larger influence on the results than scientific choices.

Acknowledgements

We are indebted to Michael Prather, Joyce Penner, Terje Berntsen and Maria Silvia Muylaert for helpful comments on earlier versions of this paper. We would also like to thank the Governments of Brazil, Belgium, Germany, Norway, the Netherlands and United Kingdom for support for participation in the MATCH process.

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